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# Feasibility Study for Low Drag Acoustic Liners Final Report

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July 2017

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# **NASA Advanced Air Transport Technology (AATT) Project**

## **Feasibility Study for Low Drag Acoustic Liners Final Report**

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# 1 Executive Summary

The feasibility of flight testing a low drag Multi-Degree of Freedom (MDOF) inlet and a Boeing Low Drag Linear (LDL) design was studied. The flight test is currently planned for the 3<sup>rd</sup> quarter 2018 on a 737MAX flight test as a potential collaborative project between Boeing and NASA. Once this testing is completed it will have matured the technology to a NASA TRL 7 level of maturity.

This report documents the design and structural analysis as a final deliverable for the Phase 1 contract activity. Also included is a community noise test plan, which is a key deliverable for Phase 2. Finally, a high-level estimate (Phase 3 deliverable) is provided for the work statement of Phases 2-4, which covers the build of two inlet test articles, planning and execution of a flight test with the test inlets, as well as data analysis and final documentation. The two test inlets will be compared to the production baseline inlet configuration. There is also a plan to test one of the inlets “hardwalled” using speed tape or some other similar tape to block the acoustic perforations.

The acoustic performance of the inlets will be demonstrated over a wide range of flight operations, corresponding to the various certified maximum takeoff and landing weights of the 737MAX. Structural integrity will be rigorously reviewed as part of the Boeing Safe-to-Fly process.

The flight test will measure the full-scale installed noise attenuation performance of the technology validating community noise benefits at the airplane level. The NASA-designed inlet and the Boeing-designed inlet community noise attenuation will be compared with baseline configurations.

## 2 Introduction/Background

A low cost, high performance nacelle acoustic liner concept has been the subject of collaborative study between NASA and The Boeing Company. There is much interest in accelerating the maturation of the NASA liner concept for possible applications to provide quieter alternatives for future commercial airplanes. In the near term this technology is a candidate for use in the X-Plane demonstrations.

Simultaneously, Boeing is interested in developing a low drag liner design. A significant milestone toward meeting the NASA and Boeing objectives will be achieved in 2018 with the completion of the planned full-scale community noise flyover test. Successful completion of the flight test will demonstrate the technology in an actual operating environment, achieving a NASA TRL 7.

### 3 Scope and Objectives

The particular airplane platform used for this study to demonstrate inlet acoustic liner effectiveness is the 737MAX. This platform is a good candidate because it is currently undergoing a flight test program, therefore Boeing flight test support resources are readily available.

The objectives of this study are:

1. Advance the NASA liner and Boeing liner technologies to NASA Technology Readiness Level 7
2. Develop inlet inner barrel engineering drawings using NASA and Boeing liner concepts
3. Complete the structural analysis and Safe-to-Fly assessment
4. Build two flight test inlets for full-scale demonstration, as well as developing potential manufacturing processes for future production implementation.
5. Create a detailed Flight Test Plan and Cost Estimate for this design maturation track.

## **4 Advanced Inlet Acoustic Liner Prototypes**

The advanced inlet acoustic liner prototype designs are based on changes from the 737MAX Inlet. The Inner Barrel will be designed such that the overall core thickness, part periphery, interfaces to adjacent structure, and installation processes and fasteners are identical to the production design.

Both inlet designs will utilize versions of the low-drag face sheet perforations that were tested on NASA's grazing flow impedance tube (GFIT) rig in 2016. The particular details of each face sheet design are contained in the engineering definition drawings. The prototype inlets will also be designed to maximize the acoustically active area.

### **4.1 NASA Prototype Acoustic Liner**

The NASA concept utilizes a lower drag face sheet design and a NASA-defined acoustic core. The final definition of the acoustic liner will be provided by NASA. A placeholder is used for the NASA-specified core in the cost estimate. A finalized estimate is dependent on the supplier's evaluation of the core build cost.

### **4.2 Boeing Prototype Acoustic Liner**

The Boeing concept utilizes a low drag face sheet design as well. The details of the liner construction are Boeing proprietary and only discussed in the Limited report. The cost estimate is reflective of process development and coupon tests required to manufacture

## 5 Acoustic Design Environment

Acoustic design environment parameters were provided to NASA on October 18, 2016 in Boeing Letter No: 9MT-3D3-105456. This package included an inlet model used for noise propagation modeling, and impedance characteristics of the 737MAX inlet liner.

## 6 Structural Assessment

A structural assessment has been completed to evaluate the feasibility for flight test worthiness of the design changes for the prototype NASA and Boeing acoustic liner designs. The following assumptions were used in the analysis:

1. Existing material systems for the face sheets.
2. Core structural properties are not significantly degraded from the production design.
3. Chosen perforation method does not result in significantly worse process control and variation (i.e. parametric and analytic assessments are valid).
4. NASA design is enveloped by the Boeing design for structural capability (i.e. face sheet POA is lower).
5. Perforations are aligned in the axial direction within the drawing tolerance.
6. Bond strength of face sheet/linear material/core is not significantly degraded from the capability of the production design.
7. Margin of safety calculations are predicated on existing Boeing analysis methods, available structural allowables, and existing internal and external structural loads.

The structural assessment consisted of the following tasks:

1. Estimate face sheet moduli of new perforation pattern
2. Update Finite Element Model (FEM) to reflect the design changes
3. Identify and evaluate critical load cases from existing 737MAX analysis
4. Estimate perforation strength knockdown for new perforation pattern
5. Evaluate changes in structural margins of safety for critical load cases
6. Identify structural testing required to characterize the capability of design changes where existing data does not exist (i.e. new processes).
7. Establish 80% confidence of safe-to-fly for planned flight test
8. Identify risks and statement of work to complete structural analysis

The assessment has shown 80% confidence that the 737MAX inlet with the implementation of the prototype acoustic liners as designed is suitable for flight test.

## 7 Test Plan

### 7.1 Testing Scope and Objectives

The purpose of the Low Drag Liner flight test plan is to gather back-to-back ground microphone data between a production inlet, hardwall inlet, NASA inlet, and Boeing inlet designs at key community noise flight conditions. Furthermore, the test is intended to be spot-check validations rather than an exhaustive mapping of the entire range of operation. The focus is on takeoff and approach conditions referenced in the Noise Certification Levels for the MAX family of airplanes.

Results will be used to validate the noise effectiveness of the low-drag lining on a full scale test bed. Data gathered from this flight test will also be used to compare NASA analytical predictions and improve prediction capability for designing X-Planes.

### 7.2 Test Article

The test article will be a 737MAX-7 flight test airplane outfitted with CFM LEAP-1B Block 2 engines.

### 7.3 Test Requirements and Acceptance Criteria

Noise measurements are very sensitive to local weather conditions (temperature, humidity, and wind). Therefore, the flight test conditions must be conducted within a certain weather window in order to be acceptable.

This includes:

- 14-dB/100 meter attenuation window (function of temperature and humidity)
- Winds
  - Maximum wind speed at 10 meters of 12 knots and maximum gusts of 15 knots
  - Maximum crosswind speed of 10 knots and maximum gusts of 12 knots
- Precipitation
  - No rain or snow during testing
  - No snow or standing water in vicinity of microphones
- No anomalous weather conditions
  - No sudden shift in delta temperature versus altitude (inversions)
  - No sudden shift in delta wind velocity versus altitude (shear layer)
  - No excessive turbulence which may cause unsteady airplane performance

Additional criteria may be defined in order to obtain acceptable data quality. The window of time for good weather is typically at day-break and lasts until late-morning.

The airplane must also be configured and flown according to the defined criteria in order to be acceptable. The required airplane performance parameters and tolerances will be

according to typical Noise regulatory requirements. The airplane shall be flown such that no transient noise sources are activated (e.g. bleed valves).

Data will be accepted if all weather and airplane performance criteria are met.

## 7.4 Test Configuration Management

The following configurations will be tested:

- 2x production inlet
- 1x Hardwalled (using speedtape) inlet
- 1x Boeing designed inlet with Low Drag facesheet installed on the test engine
- 1x NASA designed inlet with Low Drag facesheet

All of the above test configurations will be tested with a non-treated (hardwalled) forward fan case. The production inlet will have a hardwall forward fan case on one side, and a production treated forward fan case on the other side. In the event that new perforation manufacturing is not viable for the flight test hardware, a more conventional face sheet will be manufactured, meeting the POA criteria.

All of the above configurations will be managed using the Boeing standard flight change (F.C.) process. The F.C. process requires proper documentation, including engineering drawings, for all non-standard configuration changes.

## 7.5 Safety

Safety is an integral part of Boeing's culture. This includes safety of people, products and assets. Processes and procedures ensuring safe operations have been put in place and are overseen by the Boeing Safety organization. These procedures include protocols for:

- Test Readiness Reviews, including Safety of Flight Reviews and First Flight Readiness Reviews – These reviews assures readiness (procedures, planning and requirements) and authorizes flight.
- Test Plan Reviews and Sign off – These reviews involve cross-functional teams ensuring the safe execution of test plans, including identification and alleviation of any possible hazards brought about by conditions being flown.
- Flight Operation Risk Assessments – Independent reviews intended to focus on flight operations at a given site or program. These are conducted on an “as needed” basis.
- Site Safety Surveys – Checklists are produced for Site Safety

The 737MAX-7 test bed will follow the Safe-to-Fly process. At the conclusion of the process, Boeing will deliver a copy of the Safe-to-Fly review, the minutes, and review



board concerns with closed resolutions to NASA. Reviews held for the 737MAX-7 test bed will be attended by up to three NASA representatives as part of the review process. Dates of these reviews will be coordinated with NASA personnel attending the reviews.

In addition to the above, Boeing will operate the 737MAX-7 test bed in accordance with Boeing's own Aviation Safety Program. The Aviation Safety Program will be reviewed with the NASA Aviation Safety Officer (ASO) no later than 30 days prior to the first flight campaign. Concurrence with the Aviation Safety Program by the ASO will be provided at the time of that review and confirmed through email notification to the Boeing project manager. Though mutual consent between Boeing and NASA, the ASO may initiate further safety reviews, if deemed necessary.

Boeing will operate the 737MAX-7 test bed in accordance with an approved Flight Operations Manual. The Flight Operations Manual will be provided to the NASA Langley Chief of Flight Operations (CFO) no later than 30 days prior to the flight campaign to review and provide concurrence to the Boeing project manager through email. In accordance with internal operating principals, Boeing will be responsible for the physical security and safety of the aircraft, ground vehicles, NASA hardware and instrumentation, and associated equipment used in support of this task order.

## 7.6 Test Description and Conditions

The mini flyover test will be conducted at Moses Lake Airport and is anticipated to occur during the third quarter of 2018. For each test configuration, seven (7) Takeoff intercepts and four (4) Approach intercepts will be performed over the microphone arrays. Repeats will be flown for data repeatability, for a total of 22 conditions per configuration. The range of power settings on the test engine will cover enough power settings to understand the effect of the inlet for the 737MAX family.

Table 7-1 contains a preliminary categorization of flyover conditions for each configuration. The production configuration will establish a data baseline, taking data for the production inlet with treated and hardwalled forward fan case. Takeoff and Approach conditions are designed to cover key engine power settings applicable to the minor models of the 737MAX family. It is important to characterize the inlet performance over a broad range of low speed aero conditions. Furthermore, each condition will be repeated one time in order to develop a statistical average between two repeats.

Table 7-1: Matrix of Configurations and Test Conditions

Inlet Design	Flight Condition	Number of Low Power Points (-7)	Number of Med Power Points (-8)	Number of High Power Points (-9,-10X)
Production – R side	Takeoff	1	3	3
Production – R side	Approach	1	2	1
Production – L side	Takeoff	1	3	3
Production – L side	Approach	1	2	1
Hardwall	Takeoff	1	3	3
Hardwall	Approach	1	2	1
NASA Design	Takeoff	1	3	3
NASA Design	Approach	1	2	1
Boeing Design	Takeoff	1	3	3
Boeing Design	Approach	1	2	1

## 7.7 Community Noise Flight Test Procedure

Community noise testing will consist of a series of “racetrack” flight patterns, each with a different target N1 set in advance to ensure that the airplane intercepted the desired altitude over the center of the microphone array. These patterns are shown in Figure 7-1 through Figure 7-4.

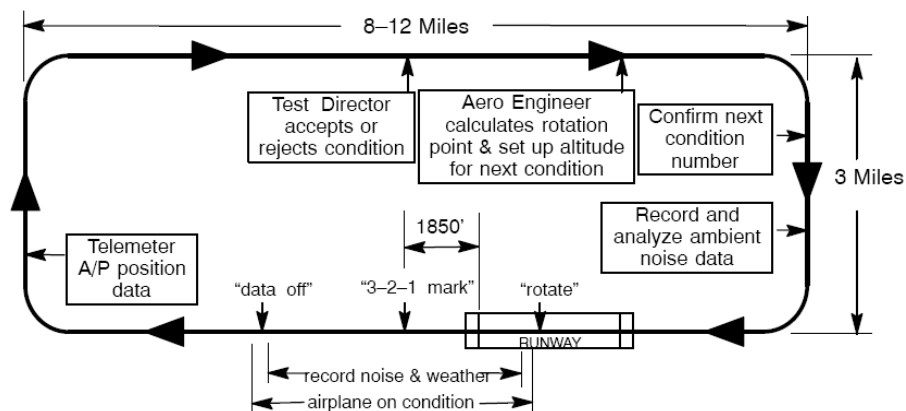


Figure 7-1 – Plan-view of “racetrack” for takeoff conditions.

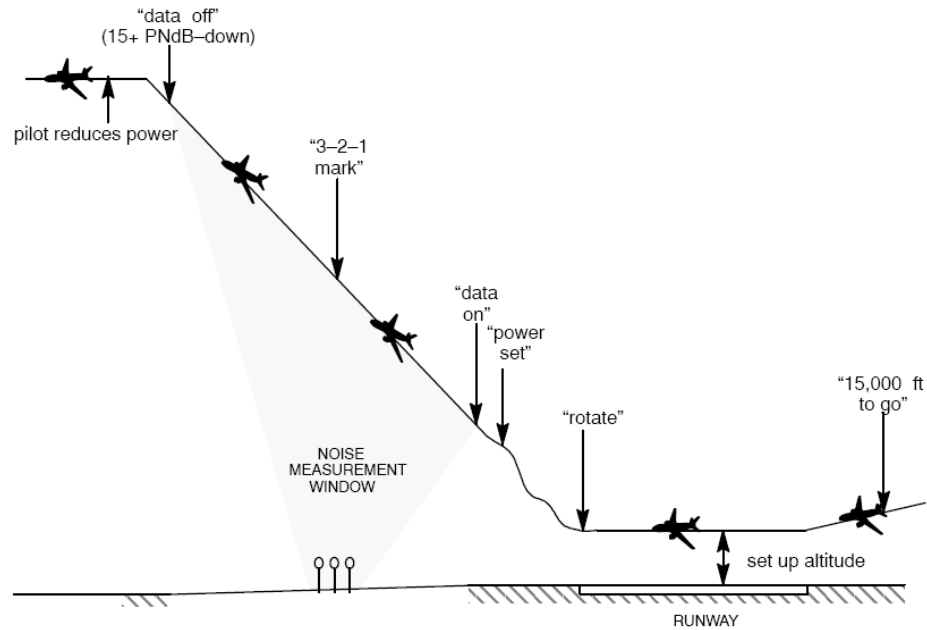


Figure 7-2 – Elevation view of “racetrack” for takeoff conditions.

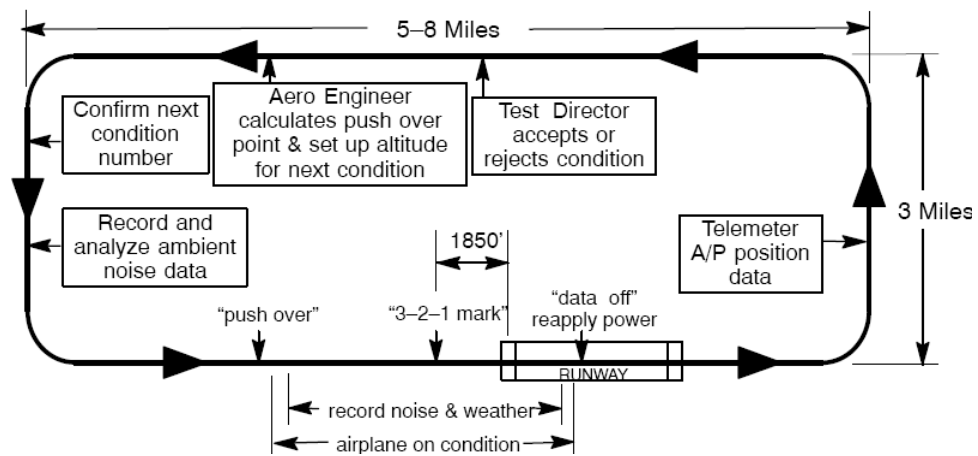


Figure 7-3 – Plan-view of “racetrack” for approach conditions.

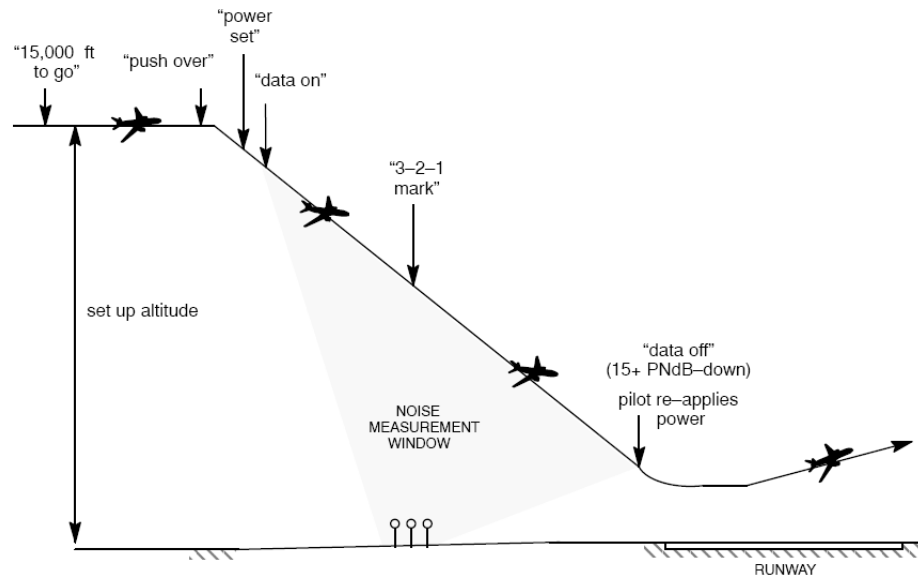


Figure 7-4 – Elevation-view of “racetrack” for approach conditions.

## 7.8 Test Analysis Plan

The Boeing Noise Lab will supply the capability for “online” data analysis, meaning data comparison plots will be displayed and printed immediately following a test conditions. The various test configurations will be compared to the baseline production inlet using a waterfall delta plot, see example in Figure 7-5. On these plots, it is easy to discern SPL increase or decrease at emission angles and frequencies of interest relative to the baseline configuration.

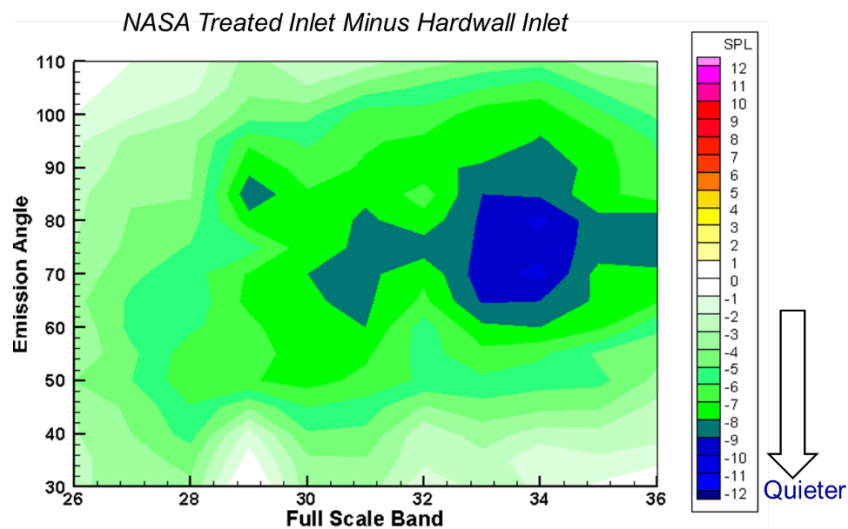


Figure 7-5: Example Delta Plot for NASA Treated inlet minus Hardwall Inlet Flight Test Data

Another useful style of data plotting is to review delta spectral power levels for the certification conditions of interest, see Figure 7-6. Once again, the delta will be relative to the production inlet baseline. This type of plot is useful because it shows a summary of broadband acoustic energy change with each inlet liner concept.

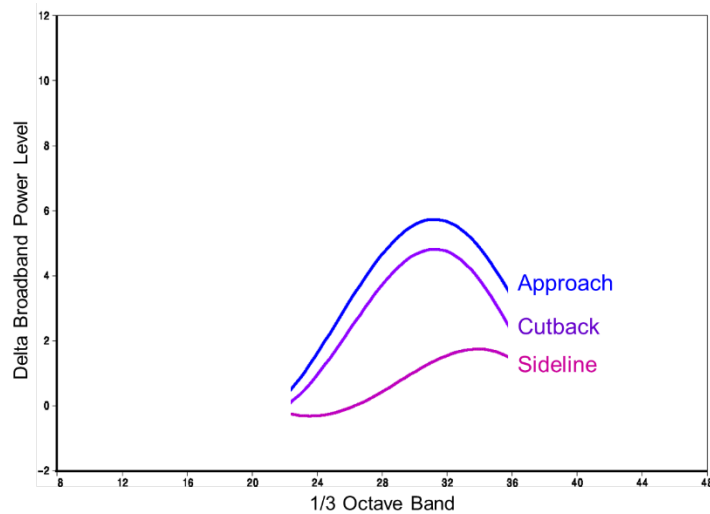


Figure 7-6: Example Delta Plot of Broadband Power Level vs. 1/3 Octave Band for flight conditions

Plots of forward arc power levels versus Tip Mach Number will also be generated, see example in Figure 7-7. With this plot it is possible to focus on the inlet-radiated noise component, consider tone impact, and compare spectral shapes between inlet design concepts.

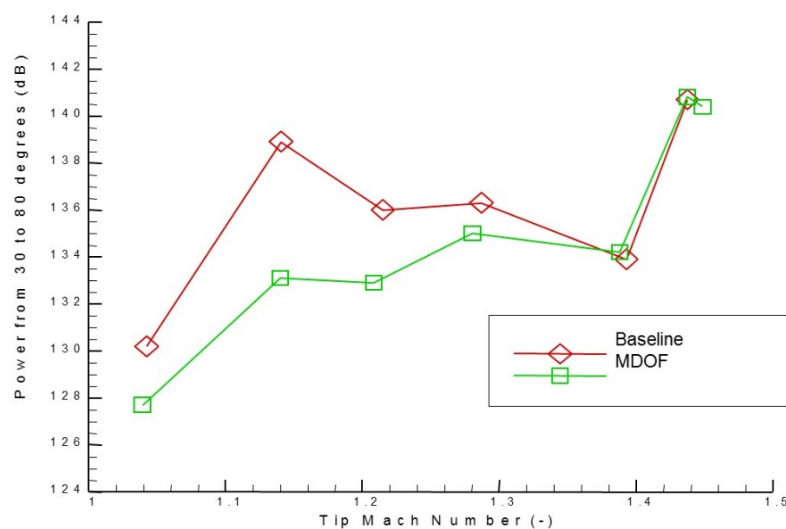


Figure 7-7: Example Plot of Forward Arc Power Levels vs. Tip Mach Number

The phased array system will provide “heatmap” type plots which help locate noise sources on the test article via beamforming. The phased array system will be monitored by Lab and Staff personnel.

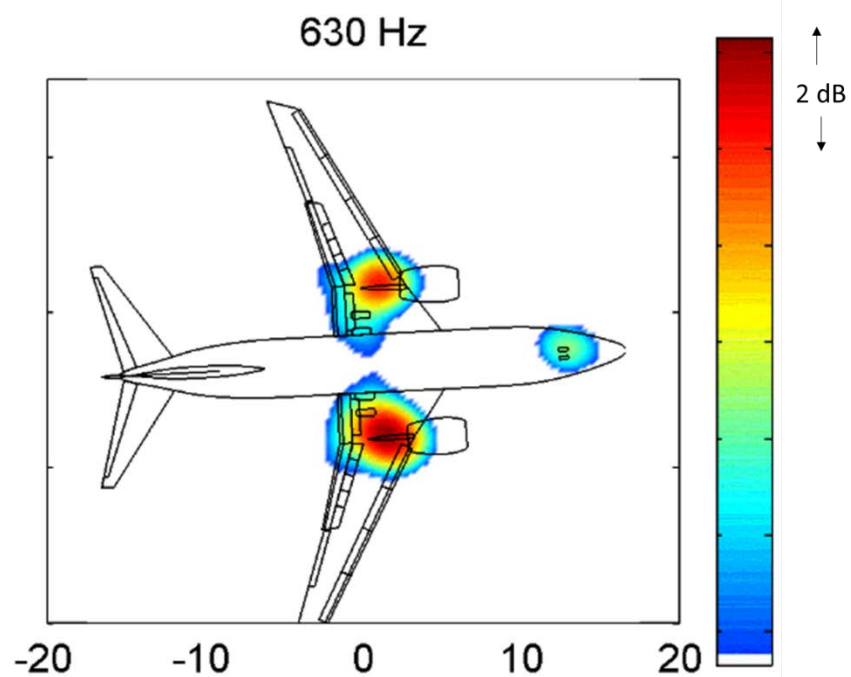


Figure 7-8: Phased array plot example at 630Hz

## 8 Schedules

Figure 8-1 contains a notional schedule for the design maturation, process development, and fabrication of two inlet inner barrels for flight test. The target end date is to deliver two test inlets for installation by June, 2018. The flight test planning, execution, data analysis, and documentation is also depicted.

There is a large effort required for the process development of perforating and bonding, which is planned to be done in tandem with structural analysis. Structural testing is on the coupon level, and coupons will be made for acoustic impedance testing. The flight test planning will occur on a parallel path with hardware development, with analysis and documentation. This schedule assumes a project kick-off date of April 1, 2017.

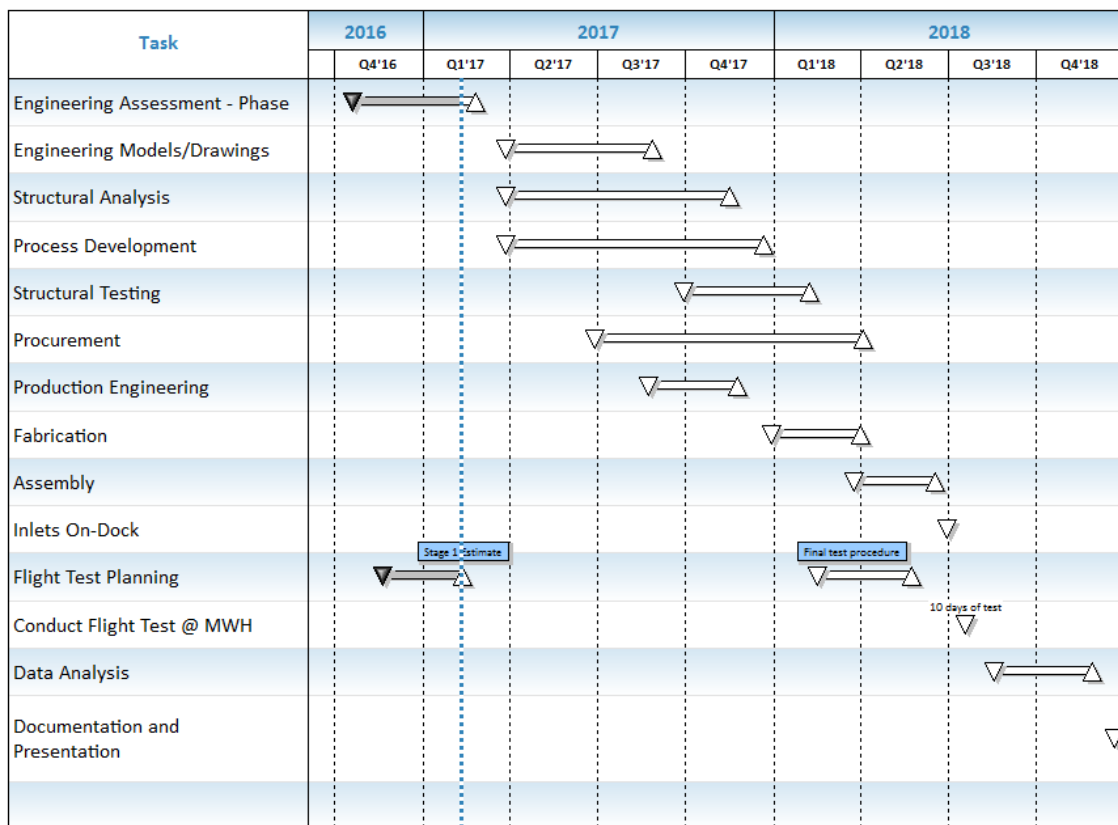


Figure 8-1: Schedule of design and build of flight test inlets, and flight test campaign

## 9 Conclusion

The prototype advanced engine inlet is an extremely promising alternative to the state-of-the-art, standard inlet lining design. Small-scale grazing flow impedance tube and wind tunnel testing demonstrates a significant drag reduction and comparable acoustic performance to an industry baseline. This liner concept has evolved into two configurations for further study: 1) NASA design, and 2) Boeing design.

These liner concepts have been adapted to a 737MAX inner barrel in order to work out the details of feasibility and installation. The prototype designs assume no change to the interfaces between the A-flange and inlet lip attachments. Furthermore, the material system is kept the same in engineering drawings so that prototype hardware can be manufactured as quickly as possible. More advanced and cost-effective materials may be considered for future applications, but a compressed schedule and use of existing manufacturing tooling drive the requirement for keeping the same material system.

Boeing has put together a development and build schedule of the two inlet configurations adapted to the 737MAX inlet. A community noise flyover test plan is also provided, to validate the acoustic performance at an airplane level. Accompanying these plans is a preliminary cost estimate for the hardware development, flight test planning and execution, and a daily rate for conducting a flight test. These cost estimates are submitted in a separate document from this report.



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